Variability of the Indian Summer Monsoon and Tropical Circulation Features

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ABSTRACT

The Indian economy is very closely linked with the variable performance of the summer monsoon. The incidence of dry and wet conditions over the country has been examined for the period 1871–1978 by examining the normal monsoon rainfall and its variability over the region by means of the Index of Dryness over India (IDI) and the Index of Wetness over India (IWI). These are respectively defined as the country's percentage area characterized by dry and wet conditions. These series are found to be homogeneous, random, highly variable and positively skewed. The year in which IDI (IWI) exceeds the mean by more than two times the mean deviation from the mean is taken as a year of large-scale drought (flood). The occurrence of large-scale droughts or floods is found to be random in time continuum.

The IDI and IWI show consistently significant correlation with the Southern Oscillation Index (SOI) and with sea surface temperature (SST) anomalies of the equatorial eastern Pacific for the concurrent and succeeding seasons. The relationships of the indices of dryness and wetness over the country with SOI and SST anomalies are expected to be useful in understanding the implications of the large-scale anomalies in the performance of the Indian summer monsoon.

1. Introduction

Agriculture, hydro-electric power, and industry in India are heavily dependent on the performance of the summer monsoon which provides 75 to 90% of the annual rainwater potential over most parts of India. The summer monsoon generally prevails over India during the period June to September. Variability is experienced in the time of onset and withdrawal of the monsoon and in the activity of the monsoon during the season. These variations, when large, critically affect the economy of the country. The behaviour of the summer monsoon over India has been studied by Blanford (1886), Walker (1910), Pramanik and Jagannathan (1953), Ramdas (1960, 1976), Rao and Jagannathan (1963), Jagannathan *et al.* (1973a,b), Parthasarathy and Dhar (1974), Rao (1976), Banerjee and Raman (1976), Ramaswamy (1976), Mooley (1975, 1976), Parthasarathy and Mooley (1978), Bhalme and Mooley (1980), Joseph (1976), Joseph *et al.* (1981), Mooley and Parthasarathy (1979, 1982, 1983), Mooley *et al.* (1981, 1982).

Within the tropics, rainfall is the most important climatic element, since in many tropical countries irrigation is meagre and crops are mostly rain-fed. The alarming increase in the population in the tropical belt has resulted in a rapidly increasing requirement for higher food production and hydro-electric power and there is a strong need to make a detailed investigation of rainfall and its variability on the basis of rainfall data available for over a century.

In this study, it is proposed to examine the variability of indices of dry and wet conditions and the incidence of large-scale droughts and floods over India during the summer monsoon season. Relationships of the indices of dryness and of wetness over India with the Southern Oscillation Index (SOI) and with sea surface temperature (SST) anomalies over the equatorial eastern Pacific have been explored and discussed.

2. Rainfall data

The high variability of tropical rainfall from place to place and from year to year makes it necessary to undertake the investigation on the basis of the data from a uniform and well-distributed network of raingauge stations for a long period. The raingauge network over India varied by two orders of magnitude, from about 50 in 1850 to about 5000 in 1970. This highly variable network affects reliability of the computed areal average of rainfall. In view of this situation, the network is so selected that there is one station in each district which has been the smallest administrative unit in India. For revenue purposes, smaller units like talukas[1] exist, but we do not have one raingauge station for each taluka of a district over a long period. A careful examination of the available rainfall record for the country indicated that if the data for these stations are taken from 1871, the data gaps will be few. The missing rainfall values for the few stations were interpolated as per the ratio method suggested by Rainbird (1967). A nearby station or the regional average of that area is selected such that its monsoon seasonal rainfall has the highest correlation

[1] There are about 6–12 talukas in a district.

with that of the station in question. The ratio method is then applied by using rainfall data of the selected station, and the missing rainfall values are interpolated. The interpolated values are less than 2% of the total. The rainfall data for the 306 raingauge stations for the period 1871–1978 have been used in this study. The network of stations is shown in Fig. 1. The network has a bias towards north India consisting of the states of Punjab, Haryana, Uttar Pradesh and Bengal, in that the network over this portion is closer than that over the rest of India. While the area of most of the districts is small, there are a few districts whose area is rather large. The average area represented by each raingauge over the country works out to be about 100 × 100 (km), but ranges from 70 × 70 in Uttar Pradesh to 150 × 150 (km) in West Rajasthan. However, it is difficult to select a raingauge network with uniform density and some arbitration is involved in assigning the weights to each of the raingauge stations. This situation is expected to introduce a relatively small error. In view of the fact that the areal representativeness of a raingauge in a hilly area is small, and the raingauge network in the hilly areas of India is generaly inadequate, the hilly areas of India consisting of Jammu and Kashmir, Himachal Pradesh, the hills of west Uttar Pradesh, Sikkim from Bengal and Arunachal Pradesh from Assam (as shown by hatching in Fig. 1) have not been considered. The area considered measures 2.88×10^6 km^2 as against the country's total area of 3.29×10^6 km^2, about 90% of the total. Hereafter, the area considered will be referred to as India or the country.

The monthly rainfall data for the 306 stations were obtained from the relevant Indian Meteorological Memoirs and the Daily Rainfall Volumes for the period 1871–1900, (further details Mooley *et al.*, 1981), from the records of the Deputy Director General of Meteorology (Climatology and Geophysics), India Meteorological Department, Pune-411005 as punched cards for the period 1901–70, and were collected from the relevant records for the period 1971–78. The 306 seasonal (June to September) rainfall series have been examined for homogeneity by Swed & Eisenhart's test runs (WMO, 1966a) for runs above and below the median and are found to be homogeneous at 5% level.

3. Indices for dryness/wetness over India and their statistical properties

It is quite rational to assume that the water-dependent economic activities in an area get adjusted to the rainwater normally available and to the vari-

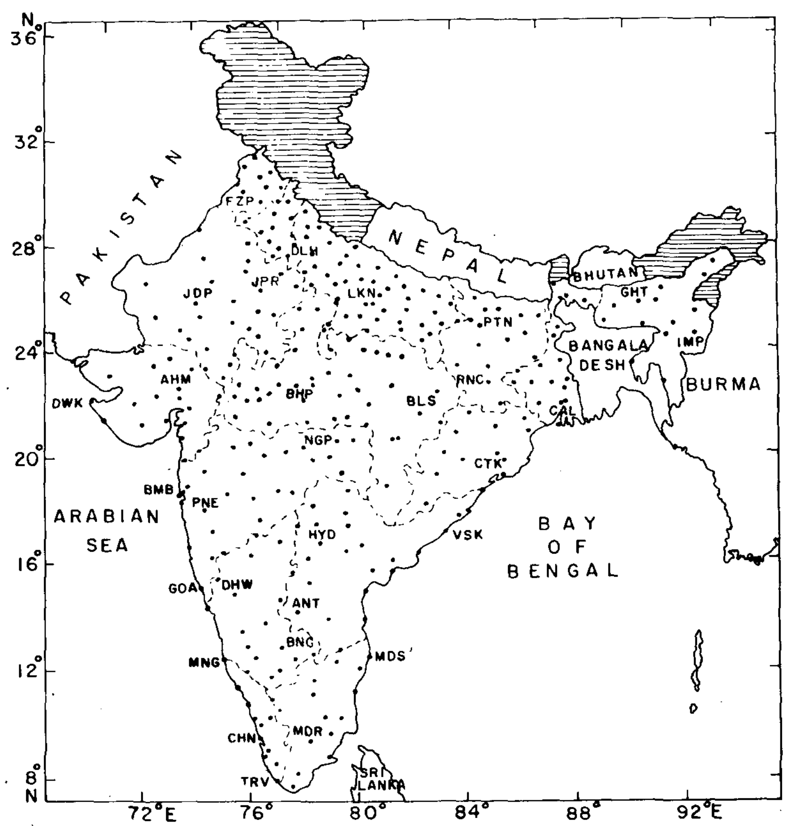

FIG. 1. Network of raingauge stations over the area considered excluding hilly area (Hatched).

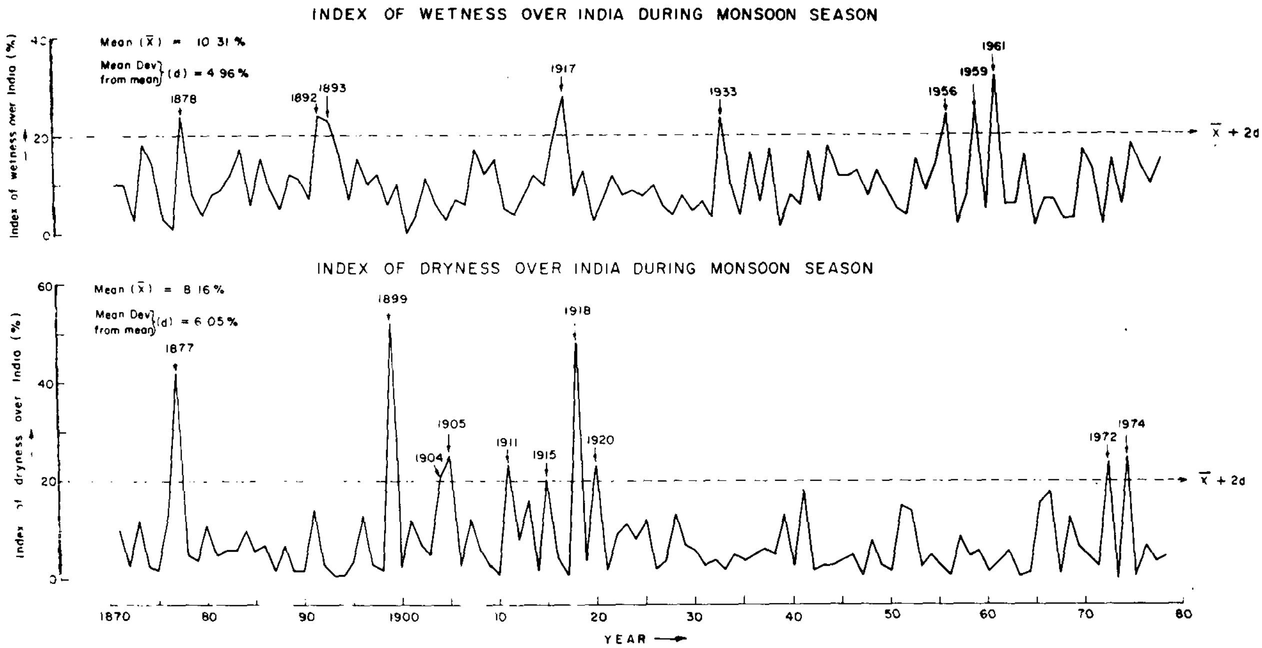

FIG. 2. Index of Dryness over India (IDI) and Wetness over India (IWI) during the summer monsoon season (June–September) 1871–1978.

ability of the rainwater. Hence it will be preferable to devise a criterion based on rainfall expressed as a standard deviate, $y_i = (x_i - \bar{x})/\sigma$ where x_i is monsoon rainfall in ith year, $\bar{x}$ is the normal monsoon rainfall and σ the standard deviation of monsoon rainfall. Adoption of such a criterion will also be helpful in following a uniform criterion over a large area in which mean rainfall and variability of rainfall vary from place to place. The criteria used for identifying drought (flood) over a district are $y_i < -1.28$ (>1.28) respectively. These values correspond to the 10% points (one sided) of the Gaussian distribution. According to the studies by Mooley & Appa Rao (1971) and Rao *et al.* (1972) monsoon seasonal rainfall is Gaussian or near-Gaussian for many stations in northeast India, east Uttar Pradesh, east Madhya Pradesh and southern half of the west coast of India. It is mostly in the low rainfall regions of India that deviations of monsoon rainfall from the Gaussian distribution are relatively large. With these conditions, rainfall at each station in each of the years is categorized as drought, flood or neither drought nor flood depending on the value of y_i. The country's area under drought in each year is obtained by adding the areas of the districts suffering from drought in that year. This area under drought in each year is expressed as a percentage of the country's area. This percentage is termed as the Index of Dryness over India (IDI) or in case of flood, Index of Wetness (IWI). We thus have a series of IDI and IWI for the period 1871–1978. These IDI and IWI series for the period 1871–1978 are shown in Fig. 2.

Both series were found to be homogeneous at 5% level by applying Swed and Eisenhart's test (WMO, 1966a) of runs above and below the median and to contain no significant trends by applying Mann–Kendall rank statistic test (WMO, 1966b).

The statistical properties of the IDI and IWI series are given in Table 1. It can be seen that while both the series show high variability and high positive skewness; the variability and positive skewness are much higher for the IDI series.

Table 2 gives the mean, standard deviation and

TABLE 1. Statistical properties of IDI and IWI Series for the period 1871–1978.

Parameter	IDI Series	IWI Series
Mean (%)	8.16	10.31
Median (%)	4.93	8.97
Upper quartile (%)	10.62	13.68
Lower quartile (%)	2.85	5.66
Extreme values (%) and corresponding years	0.6, 51.6 1910, 1899	0.5, 32.3 1901, 1961
Mean deviation from the mean (%)	6.05	4.96
Mean deviation from the median (%)	5.34	4.89
Standard deviation (%)	8.95	6.30
Coefficient of variation (%)	109.7	61.1
$g_1/SE(g_1)$*	11.51	4.24
$g_2/SE(g_2)$*	19.27	1.88
Auto-correlation coefficient	−0.16	−0.08

* Note g_1 and g_2 are Fisher's coefficients of skewness and kurtosis.

TABLE 2. Mean, standard deviation (SD) and coefficient of variation (CV) of IDI and IWI for different decades.

	IDI			IWI		
Period	Mean (%)	SD (%)	CV (%)	Mean (%)	SD (%)	CV (%)
1871–80	10.40	11.02	106.0	9.47	7.00	73.9
1881–90	5.05	2.54	50.3	10.47	3.56	34.0
1891–1900	9.66	14.66	151.8	12.96	5.98	46.1
1901–10	9.54	7.68	80.5	8.10	5.14	63.5
1911–20	14.82	13.96	94.2	11.02	7.37	66.9
1921–30	7.21	3.72	51.6	7.70	2.21	28.7
1931–40	4.96	2.98	60.1	9.95	6.80	68.3
1941–50	5.07	4.86	95.9	11.48	3.90	34.0
1951–60	6.33	4.66	73.6	11.09	7.63	68.8
1961–70	7.37	5.83	79.1	9.98	8.93	89.5
1971–78	8.81	8.40	95.4	11.11	5.36	48.2

coefficient of variation of the IDI and IWI values for each decade.

It is observed that the highest IDI decadal mean is 14.8 in 1911–20 and the lowest of 5.0 in 1881–90 and 1931–40; the highest and the lowest values of CV of 152% and 50% are for the decades 1891–1900 and 1881–90, respectively. For IWI, decadal means of 13.0 and 7.7 for the decades 1891–1900 and 1921–30, respectively, are highest and lowest values; the highest and the lowest values of CV of 89% and 29% are for decades 1961–70 and 1921–30, respectively. In view of the relatively low values of IDI and IWI and their low variability, the decade 1921–30 can be considered to be the decade of best performance of the monsoon.

4. Power spectrum analysis of the series

Power spectrum analysis of the IDI and IWI series has been carried out by following the procedure as given in WMO Technical Note (1966b) in order to determine significant cycles, if any, in these series. The maximum lag of $m = 35$ has been used. The correlogram and the spectrum are shown in Fig. 3. The spectrum analysis was also carried out on each of the two halves of the series with the maximum lag of 15.

From Fig. 3 it is seen that for the whole IDI series, there are two peaks, one at 2.3 years and the other at 2.7 years, both significant at 10% level only. However, the spectrum of each of the two halves of the IDI series does not show any peak significant even at 10% level. This suggests the absence of any consistently significant cycles in the IDI series.

For the whole IWI series we find significant peaks at 2.8 years (significant at 1% level), at 2.9 years (significant at 5%) and at 2.3 years (significant at 10%), but none significant in the first half of the series, and one at 2.8 years (significant at 5%) in the second half of the series. Further examination of the three parts of the series does not suggest any consistently significant cycle in the IWI series.

5. Large-scale droughts/floods

As long as IDI or IWI values are small, there is little effect on the economy of the country, but it makes an impact when the value is large. If the mean value is m, and d is the mean deviation from the mean, then a value of IDI (IWI) in excess of $(m + 2d)$ is taken as the criterion for identifying large-scale drought (flood). For both series, $(m + 2d)$ is very close to 20.25%, and a value exceeding 20% has been adopted as the criterion for identifying large-scale drought or flood. Fig. 2 shows this 20% limit and the years of large-scale drought and flood during the period 1871–1978. There are ten large-scale droughts years, namely 1877, 1899, 1904, 1905, 1911, 1915, 1918, 1920, 1972 and 1974, and eight large-scale flood years, 1878, 1892, 1893, 1917, 1933, 1956, 1959 and 1961. It is seen that the large-scale droughts of 1877, 1899 and 1918 affected 40–50% of the country, whereas in the remaining seven large-scale droughts only 20–25% of the country was affected. The worst flood year on record is 1961 when 32% of the country was affected by floods. In the remaining seven years, 20–25% of the country was affected by floods. By applying the Mann–Kendall rank statistic and Swed & Eisenhart's tests to the large-scale drought and flood years series of India, it is observed that the occurrence is randomly distributed in time continuum.

6. IDI/IWI and the Southern Oscillation

A large number of famines resulting from droughts in the 19th century and their adverse impact on the Indian economy and the acute suffering of the people were responsible for the urgent need felt by the Government of India for obtaining an advance estimate of the performance of the summer monsoon over India. This ultimately led to the establishment of the India Meteorological Department in 1875. Since then attempts have been made to forecast the summer monsoon rainfall. Sir Gilbert Walker was the first meteorologist who systematically examined the relationship of the monsoon rainfall with large-scale circulation features and in 1906 developed a regression equation based on this relationship for estimation of the monsoon rainfall. Thereafter, efforts have been made in India for the search of better and stable predictor parameters.

With greater understanding of the monsoon it was realized by the meteorological community that the monsoon is a large-scale phenomenon having interactions with the circulation elsewhere, and there has been a recent growth of interest in the monsoon, its performance, its relationship with tropical and extra-

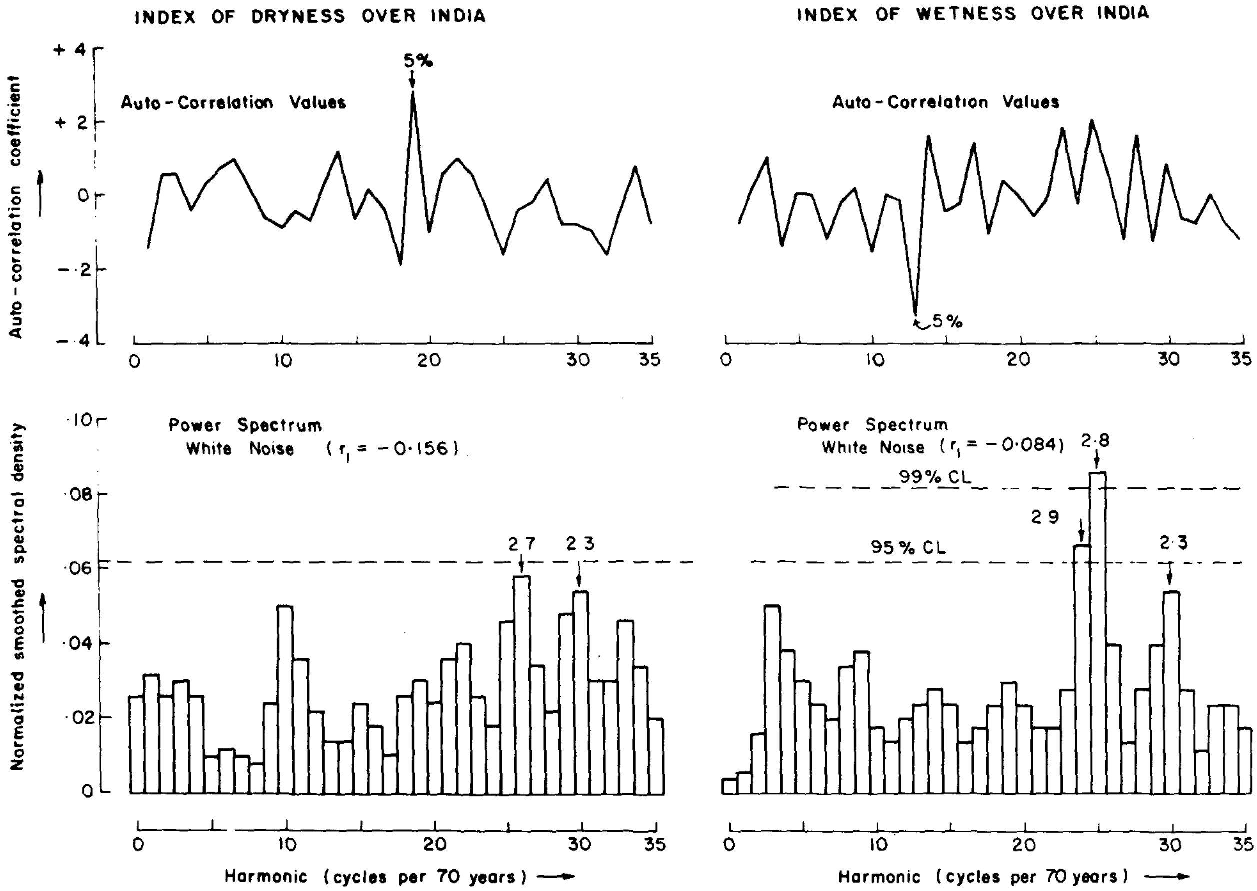

FIG. 3. Correlogram and spectrum analysis of IDI and IWI for the period 1871–1978.

tropical circulations, and estimation of monsoon rainfall. A number of studies have been made to explore the relationship between the monsoon rainfall and an index of tropical circulation generally referred to as the Southern Oscillation Index (SOI)—Walker (1923, 1924), Walker and Bliss (1932), Troup (1965), Berlage (1966), Krishnamurty (1971), Wright (1975, 1977), Trenberth (1976), Tsuchiya (1978), Sikka (1980), Angell (1981), Fleer (1981), Pant and Parthasarathy (1981), Nicholls (1981) and Rasmusson and Carpenter (1982).

a. Wright's series

Wright (1975) devised an index to represent atmospheric variations of the Southern Oscillation (SO) based on pressure data of eight stations in the latitudinal zone 30°S–20°N. He performed principal component analysis on these eight pressure series and for each of the seasons obtained the dominant component of SO, the first eigenvector coefficient. This was standardized to mean zero and standard deviation unity (for further details see Wright's paper). The time series consisting of these dimensionless numbers are homogeneous and correspond with the behaviour of the Southern Oscillation in every season (Fleer, 1981). The Wright's index series for the standard 3-month seasons, DJF, MAM, JJA and SON are available for the long period (1851–1974); therefore, it was decided to examine their relationship with IDI and IWI series.

Persistence or auto-correlations in the individual series should be considered when assessing significance of cross correlation between two concurrent series (Quenouille, 1952; Sciremammano, 1979). The auto-correlations up to 5 lags for all the meteorological parameters are shown in Table 3. For IDI and IWI, none of the lag correlation coefficients up to lag 5 are significant even at the 10% level. The value of N', the effective number of independent observations, has been calculated from values of these serial correlation coefficients as per Quenouills (1952) and are given in Table 3. It is found that N', differed little from N; in many cases N' was even greater than N. In view of this situation, we used ($N - 2$) instead of ($N' - 2$) as the degrees of freedom in assessing significance of the correlation coefficient between two series in this study.

TABLE 3. Auto-correlation coefficients of the parameters used in the study.

Parameter	Period of data	Number of years	Serial correlation of the parameter Lag-1	Lag-2	Lag-3	Lag-4	Lag-5	N′ with IDI	N′ with IWI
IDI	1871–1978	108	−0.156	+0.065	+0.051	−0.039	+0.047	—	—
IWI	1871–1978	108	−0.084	+0.025	+0.102	−0.142	+0.002	—	—
SOI: DJF	1871–1974	104	−0.006	−0.122	+0.002	−0.043	−0.050	105	103**
SOI: MAM	1871–1974	104	+0.186	−0.148	+0.036	+0.042	−0.124	114	108
SOI: JJA	1871–1974	104	+0.149	−0.215*	−0.007	+0.068	−0.079	114	110
SOI: SON	1871–1974	104	+0.017	−0.192	−0.019	+0.001	−0.027	108	106
SST: DJF	1871–1978	108	+0.155	−0.113	+0.025	−0.061	−0.092	115	109
SST: MAM	1871–1978	108	+0.265*	+0.014	+0.072	+0.012	+0.061	116	112
SST: JJA	1871–1978	108	+0.079	−0.091	−0.114	+0.012	+0.057	113	103
SST: SON	1871–1978	108	+0.055	−0.101	+0.013	−0.075	−0.033	111	107

* Significant at 5% level.
** The values of N' (effective number of observations) smaller than N (actual length of the series) are underlined.

Wright's SOI series for different seasons have been tested for homogeneity by applying Swed & Eisenhart's test runs. It is found that Wright's SOI series for all seasons are generally homogeneous at the 5% level.

b. Relationship with Wright's series

Table 4 gives the coefficient of correlation (CC) between IDI (IWI) with Wright's SOI for the preceding season, DJF, MAM, the concurrent season JJA, and the succeeding season, SON for the whole period, for 60-year and 30-year component periods.

1) The relationship between the following parameters remained significant at least at the 5% level during the whole or component 30- or 60-year periods.

(i) IDI and SOI for the seasons JJA and SON.
(ii) IWI and SOI for the seasons JJA and SON.

2) During the period 1871–1900, the four relationships between IDI (IWI) and SOI for seasons JJA (SON) were significant at 0.1% level; of these, the two relationships between IWI and SOI for seasons JJA and SON continued to be significant at 0.1% level during the period 1901–30. However, after 1930 the relationship between IWI and SOI for the season SON persisted at 0.1% level of significance, but that between IWI and SOI for the season JJA fell in significance to the level of 5%.

3) The closest, most consistent and most significant (0.1% level) relationship is that between IWI and SOI for the following season SON, but this is of little interest for prediction purposes.

c. Variation in the relationship during the period 1871–1974

Starting from the year 1871, CCs between IDI (IWI) and SOI series for the preceding seasons DJF and MAM, concurrent season JJA, and the succeeding season SON have been computed for sliding-window width of 10-, 30- and 60-year periods contained

TABLE 4. Correlation between IDI (IWI) and Wright's (1975) SOI for the seasons DJF (preceding), JJA (concurrent) and SON (succeeding) during whole period and components of the whole period.

		IDI		CC between IDI & Wright's SOI for season				IWI		CC between IWI & Wright's SOI for season			
Period	Number of years	Mean	Standard deviation	DJF	MAM	JJA	SON	Mean	Standard deviation	DJF	MAM	JJA	SON
1871–1974	104	8.16	8.95	0	−0.27**	−0.49***	−0.49***	10.31	6.30	0.03	0.31**	0.50***	0.61***
1871–1930	60	9.45	10.52	0	−0.32**	−0.52***	−0.53***	9.95	5.80	0.09	0.38**	0.58***	0.68***
1901–1960	60	7.99	8.08	−0.09	−0.28*	−0.34**	−0.41***	9.85	6.03	0.25*	0.37*	0.50***	0.55***
1915–1974	60	7.81	8.10	0.03	−0.18	−0.32**	−0.34**	10.31	6.72	0.08	0.25*	0.48***	0.59***
1871–1900	30	8.37	10.95	−0.01	−0.37*	−0.69***	−0.67***	10.96	5.88	−0.16	0.31†	0.58***	0.73***
1901–1930	30	10.53	9.97	0.02	−0.27	−0.33†	−0.36*	8.94	5.54	0.34†	0.45*	0.62***	0.65***
1931–1960	30	5.45	4.30	−0.22	−0.27	−0.42*	−0.51**	10.84	6.35	0.10	0.27	0.38*	0.44*
1945–1974	30	7.35	6.66	0.12	−0.08	−0.44*	−0.34†	10.44	7.15	−0.10	0.20	0.41*	0.59***

*** Significant at 0.1% level.
** Significant at 1% level.
* Significant at 5% level.
† Significant at 10% level.

in the total period of 1871–1974, the sliding length of the periods being an interval of one year. This approach is similar to that by Trenberth (1976). Figs. 4 and 5 show the CC for each of the 10-year periods for IDI and IWI respectively. In these diagrams the CC value for a particular sliding interval is plotted against the first year of the interval. It can be seen that for 10-year periods the CC has jumped considerably, from high positive to high negative. Such a change in CC could be attributed to noise in the data series. Even one value out of 10 can result in such jumps. It may be mentioned that external factors are at times having independent effects upon one of the time series. This means that a consistently significant relationship through time is exceptional.

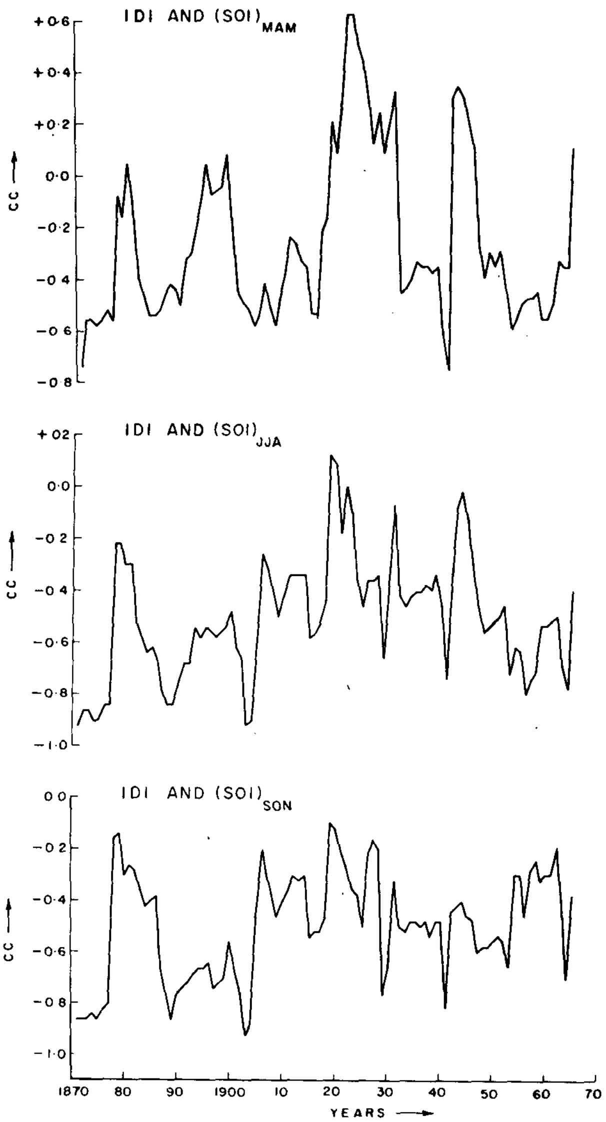

FIG. 4. Variation in correlation coefficient (CC) between IDI and Wright's Southern Oscillation Index (SOI) over the period 1871–1978 (10-year sliding window used).

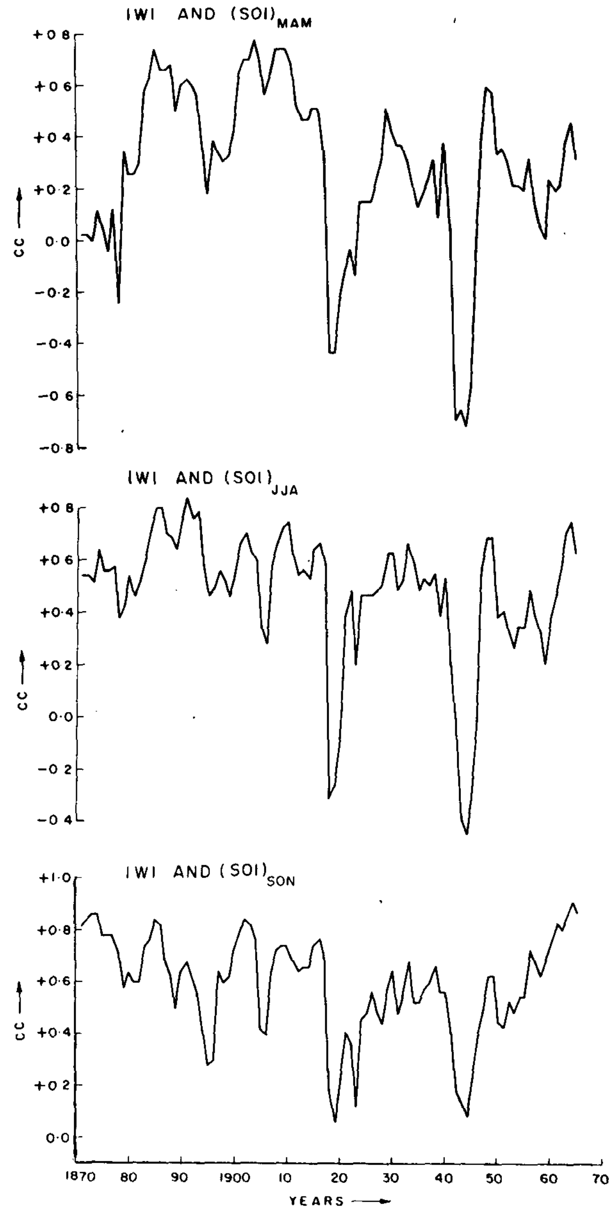

FIG. 5. Variation in CC between IWI and Wright's SOI over the period 1871–1974 (10-year sliding window used).

The highest and the lowest values of CC for 30- and 60-year sliding-window width periods during the total period 1871–1974, commencing from 1871 and sliding length by one year have been computed. From these values it is seen that if we consider any 60-year period, the following important statements can be made about the significance of the relationships.

1) The relationships between pairs of the parameters IWI–SOI for JJA, and IWI–SOI for SON continue to be significant at the 0.1% level. This stability in the significance of the relationships is remarkable and is rather rare.

2) The relationship between IDI and SOI for SON is significant at least at the 1% level.

3) The relationship between IDI and SOI for JJA is significant at least at the 5% level.

4) The most consistent and significant relationship is that between IWI and SOI for the season SON.

A remarkable example of the fall in the significance of relationship over 30-year period from very high significance (0.1% level) to almost no relationship is provided by the relationship between IWI and SOI for the season MAM over the periods 1888–1917 and 1923–52 when the correlation coefficient fell from 0.66 to 0.05. Thus while SOI for MAM could be usefully employed as a parameter to estimate IWI, a rainfall-based predictand, during the period 1888–1917, it has become totally useless for this purpose during the period 1923–52. Apparently rainfall is now being influenced by a number of parameters which may be due to some major changes in the regimes of the general circulation of the atmosphere.

d. Wright's index in years of large-scale drought/flood

Having seen the consistently significant relationship between IDI (IWI) and Wright's SOI for the concurrent season and the succeeding season as brought out by the correlation coefficients, it was decided to examine values of Wright's SOI in extreme years, i.e., in years of large-scale drought and flood. On such an examination, it is seen that in years of large-scale drought, SOI is invariably negative and in years of large-scale flood it is invariably positive. The means for the groups of large-scale drought years and large-scale flood years are given below:

Wright's SOI (group mean) for

Large-scale drought years			Large-scale flood years		
Preceding MAM	Concurrent JJA	Succeeding SON	Preceding MAM	Concurrent JJA	Succeeding SON
−0.65	−1.06	−0.94	0.75	1.22	1.44

The contrast for the concurrent and the succeeding seasons is much more than that for the preceding season.

7. IDI (IWI) and the sea surface temperature (SST) anomalies in the Equatorial Eastern Pacific

On account of the interaction between atmosphere and sea at the air–sea interface circulation systems of the atmosphere and the ocean are coupled (WMO, 1977). The latent and sensible heat fluxes from the ocean to the atmosphere constitute a significant energy source for the atmospheric circulation. On the other hand, momentum transfer and heat fluxes from the atmosphere to the ocean make a contribution towards oceanic circulation. Studies by Khandekar (1979), Weare (1979) Joseph (1981), Webster (1981), Kung and Sharif (1982), Keshavamurty (1982) and Rasmusson and Carpenter (1982, 1983) have brought out the role of SST in tropical and equatorial oceans in modifying the atmospheric circulation and in the distribution of cloudiness and precipitation. Bjerknes (1969), Rowntree (1972) and Shukla (1975) have shown that the atmosphere is much more closely coupled to the state of the underlying ocean in the tropics.

Angell (1981) has used the seasonal sea surface temperature (SST) anomaly over the region of the Pacific, 0–10°S, 180–90°W and examined its relationship with atmospheric temperature, circulation, rainfall and trace-constituent amount. The same seasonal SST anomaly data which we obtained from him have been utilized by us in examining the relationship with IDI/IWI. On applying Swed and Eisenhart's test runs, it is seen that the SST series are homogeneous.

a. Relationship between IDI/IWI and SST

Table 5 gives the CCs between IDI or IWI and SST. It is seen that relationships between IDI (IWI) and SST for seasons JJA and SON are generally significant at least at the 5% level. The correlation between IDI and SST is positive, but that between IWI and SST is negative. Higher than average SST is associated with higher than average IDI, i.e., with lower than average monsoon rainfall. The 60-year period for which this relationship is best is 1871–1930.

b. Variation in the relationship during the period 1871–1978

To examine the periods of highest and lowest values of CC for 10-, 30- and 60-year periods during the total period 1871–1978, CCs were computed for these periods sliding from 1871 onwards. The values of CC for 10-year periods are shown in Fig. 6 and 7 for IDI and IWI respectively.

It is seen that for a 60-year period the relationships between IDI and SST for the season SON and between IWI and SST for the seasons JJA and SON are consistently significant at least at the 1% level, the best relationship being that between IDI and SST for SON.

The relationship between IDI and SST is direct but that between IWI and SST is inverse. The associations between IDI (IWI) and SOI are closer than those between IDI (IWI) and SST because the SOI is based on meteorological conditions over an area which is much wider than that over which SST is considered. However, these two parameters, SST and SOI, are inter-related. The extensive monsoon trough is north of 20°N. The above average value of the pressure index (SOI) over the zone (i.e. 30°S to 20°N) indi-

TABLE 5. Correlation between IDI (IWI) and eastern equatorial Pacific Ocean SST Anomaly for the preceding seasons, DJF and MAM, concurrent season JJA and succeeding season SON, during whole period and component periods.

Period	Number of years	CC between IDI and SST Anomaly for				CC between IWI and SST Anomaly for			
		DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
1871–1978	108	−0.10	0.15	0.36***	0.51***	0.01	−0.24	−0.41***	−0.44***
1871–1930	60	−0.07	0.21†	0.39**	0.59***	−0.04	−0.28	−0.37**	−0.48***
1901–1960	60	−0.05	0.03	0.27*	0.42***	−0.18	−0.28*	−0.38**	−0.38**
1919–1978	60	−0.12	0.13	0.31*	0.35**	0.09	−0.16	−0.40***	−0.39**
1871–1900	30	−0.09	0.31†	0.49**	0.63***	0.21	−0.20	−0.41*	−0.47**
1901–1930	30	−0.02	0.12	0.34†	0.58***	−0.42	−0.43*	−0.40*	−0.57**
1931–1960	30	0.20	0.26	0.36*	0.33*	−0.06	−0.29	−0.42*	−0.27
1949–1978	30	−0.21	0.18	0.48**	0.51**	0.08	−0.23	−0.47**	−0.50**

*** Superscripts as in Table 4.

cates possibly a greater inflow of air into and around the monsoon trough, resulting in more than average rainfall over India and consequently more than average IWI value. When the SOI is below average (i.e. weak Walker circulation) and SST values over the equatorial central Pacific are higher, there is less than normal inflow around the monsoon trough and, consequently, less than average rainfall over India and more than average IDI value. While physical understanding is possible for concurrent relationships, lag relationships are difficult to explain. However, these lag relationships are evidently related to the overall evolution of the Southern Oscillation and SST (Rasmusson & Carpenter, 1982).

c. The SST during years of large-scale drought/flood

On examining the SST anomaly over the eastern equatorial Pacific, it is found that during years of large-scale drought SST anomalies in most cases are positive for the seasons, preceding MAM, concurrent JJA and succeeding SON, whereas in years of large-scale flood it is mostly negative. The mean SST anomaly for large-scale drought/flood year is given below.

Mean SST anomaly

Large-scale drought year			Large-scale flood year		
Preceding MAM	Concurrent JJA	Succeeding SON	Preceding MAM	Concurrent JJA	Succeeding SON
0.20	0.42	0.89	−0.28	−0.23	−0.50

The contrast increases from the season MAM to SON. It is rather marked for SON.

It is seen from the above analysis that some relationship exists between SST anomaly and the IDI (IWI) series. This is due to the tropical circulation system of the atmosphere and the eastern Pacific Ocean being strongly coupled through interactions at the air–sea interface. This is shown clearly by Bjerknes (1969) in a study for mid-Pacific equatorial station, Canton Island.

It should be emphasized (as per the findings of Rasmusson and Carpenter, 1983) that these relationships are probabilitic in nature. While a significant relationship appears to exist between warm episodes (SST) and the Indian summer monsoon, there are undoubtedly other factors, both local and remote, which can modify or even over-ride the typical warm episode forcing pattern. Furthermore, individual warm episodes may differ in important respects, e.g., the degree of follow-through of positive SST anomalies into the central Pacific after the initial warming near South America.

8. Conclusions

• The IDI and IWI series which are respectively measures of dryness and wetness over India during the summer monsoon exhibit high variability and high positive skewness.

• Large-scale droughts (floods) as defined by the specific criterion of IDI (IWI) are found to have occurred in 10 (8) years during the period 1871–1978.

• The following relationships between IDI (IWI) and SOI or SST remain consistently significant at least at the levels noted against them:

1) IWI and Wright's SOI for season JJA/SON at 0.1%,
2) IDI and Wright's SOI for the season SON at 1%,
3) IDI and Wright's SOI for the season JJA at 5%,
4) IDI (IWI) and SST for the season SON, and IWI and SST for the season JJA at 1%,
5) IDI and SST for the season JJA, at 5%.

• The closest and the most consistently significant relationship is that between IWI and Wright's SOI for the season SON.

• Marked changes in significance of relationship over a 30-year period are found to occur. These may be due to major changes in circulation regimes in the atmosphere during the period.

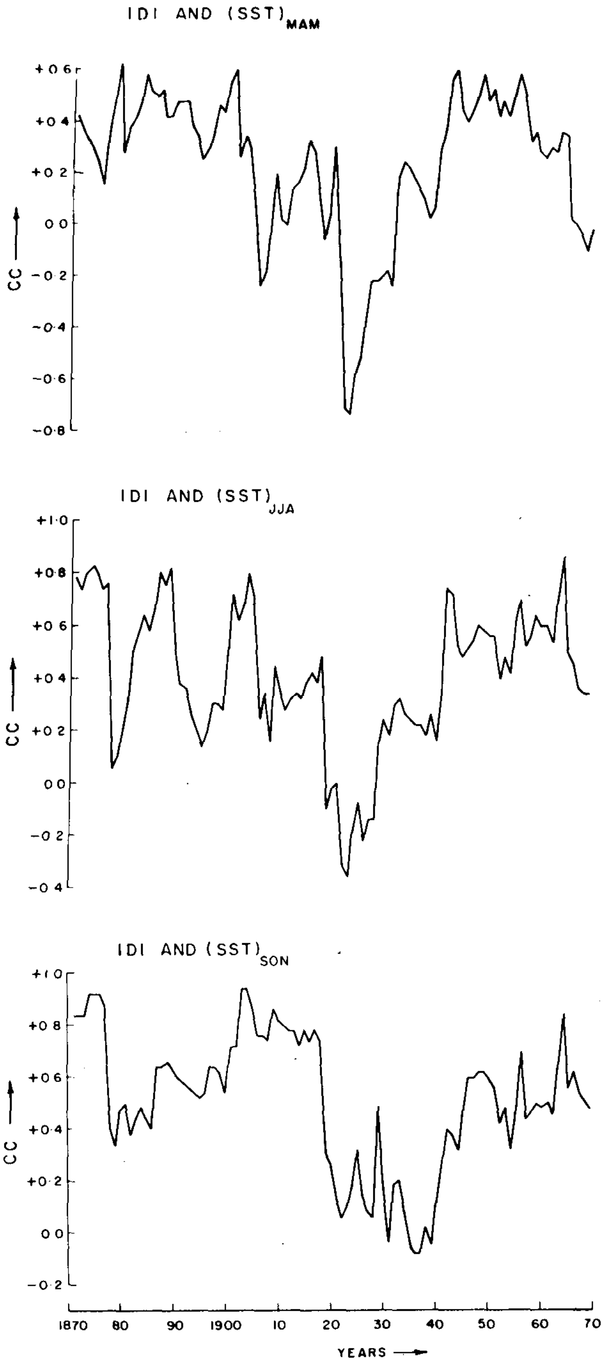

FIG. 6. Variation in CC between IDI and sea surface temperature (SST) anomaly over eastern equatorial Pacific during 1871–1978 (10-year sliding window used).

• A higher than average value of Wright's SOI for JJA suggests higher than average value of pressure to the south of the monsoon trough and possibly a greater inflow of air into and around the monsoon trough which may lead to more than average rainfall over India, i.e., more than average value of IWI, or less than average value of IDI. In this way, the concurrent significant relationship between IDI (IWI) and Wright's SOI can be physically understood.

• A warmer equatorial eastern Pacific Ocean would suggest upward air motion over this area, and this upward moving air may ultimately compensate for

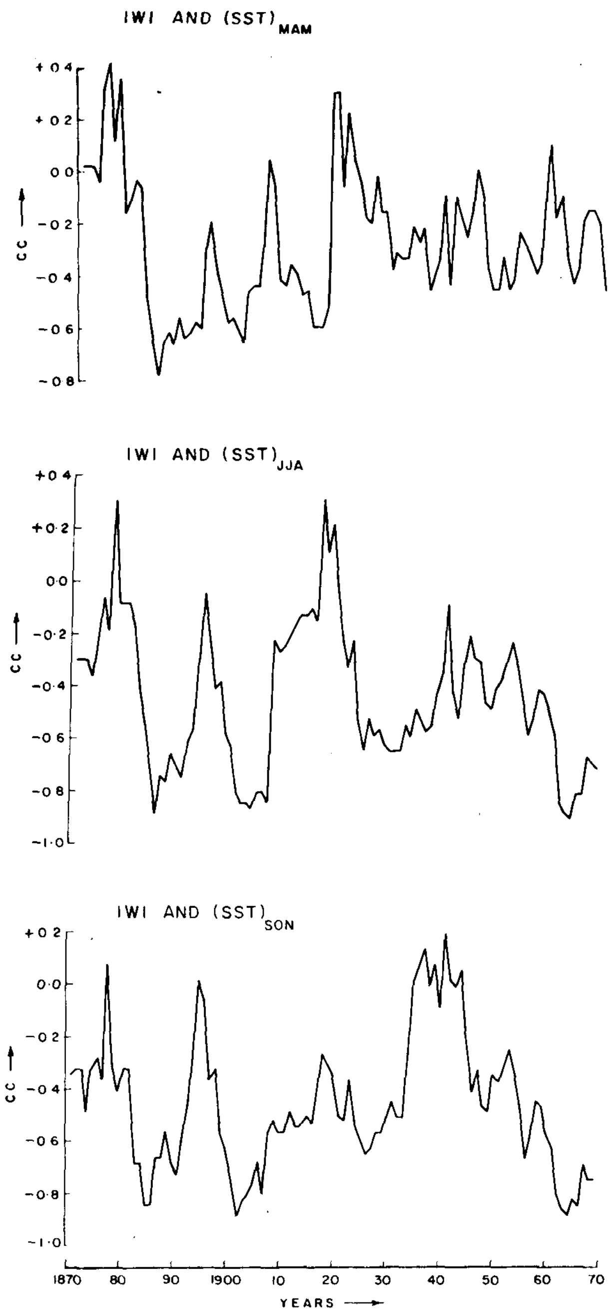

FIG. 7. Variation in CC between IWI and SST anomaly over eastern equatorial Pacific during 1871–1978 (10-year sliding window used).

decreased ascent over the eastern Indian Ocean or the western Pacific Ocean, leading to reduced activity of the summer monsoon, or a higher (lower) than average IDI (IWI).

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